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Electrical and Magnetic Properties of D6ac Steel

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ABSTRACT

The room temperature electrical and magnetic properties of the high strength steel D6ac are documented in this report. These data were used to support a wider study on the application of magnetic rubber testing (MRT) for the structural integrity management of the RAAF F-111 aircraft. While the immediate purpose of this report is to provide documented supporting data for MRT applied to the F-111 application, the results will also benefit more general investigations on the use of magnetic and electromagnetic methods for non-destructive testing of high-strength steels.

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Executive Summary

The specialised non-destructive inspection technique of magnetic rubber testing (MRT) has been used to detect fatigue cracks and other structural defects in ultra high strength D6ac steel airframe components of the F-111 aircraft for over 30 years. Despite the apparent maturity of the technique, there remain a number of significant uncertainties in the quantitative understanding of magnetic rubber testing of D6ac steel, particularly in relation to the performance of MRT using residual magnetic fields and in specifying the magnetic fields required for particular inspections. These uncertainties cannot be resolved without detailed information on the magnetic properties of D6ac.

Following an extensive search, it became apparent that there was no detailed information on the magnetic properties of D6ac in the published scientific and technical literature. It was therefore necessary for DSTO to arrange to have these properties measured directly using test specimens heat-treated to the same condition as components in the F-111 airframe.

In this technical note, the room-temperature magnetic properties of D6ac steel typical of RAAF F-111 aircraft construction are documented, including the normal induction curve, magnetic permeability, hysteresis curves and variation of magnetic remanence with applied magnetic field strength. The electrical properties of D6ac are also presented, together with formulae for the electromagnetic skin depth applicable to eddy-current non-destructive inspection of D6ac.

The magnetic and electrical properties were found to be similar in general form to those of other high-strength steels, such as SAE 4340. However they were not sufficiently alike that SAE 4340 steel can be substituted when developing or validating electromagnetic test procedures intended for D6ac components.

The significance of the results for the practice of MRT for D6ac is also briefly discussed and will be reported in more detail elsewhere.

Abbreviations and Symbols

ASTM	American Society for Testing and Materials
B	Magnetic Induction/Magnetic Flux Density
B_r	Remanent Flux Density
CGS	Centimetre-Gram-Second System of Units
δ	Electromagnetic Skin Depth/Standard Depth of Penetration
emu	Electromagnetic Unit
G	Gauss (CGS Unit for Magnetic Flux Density)
$\mathbf{H}$	Magnetic Field Strength
H_c	Coercive Force
IACS	International Annealed Copper Standard (Unit of Conductivity)
μ_0	Permeability of Free Space
μ_i	Initial Relative Permeability
μ_{max}	Maximum Relative Permeability
μ'_{max}	Maximum Differential Relative Permeability
μ_r	Relative Magnetic Permeability
μ'_r	Differential Relative Permeability
$\mathbf{M}$	Magnetisation
MRT	Magnetic Rubber Testing
NMI	National Measurement Institute
Oe	Oersted (CGS Unit for Magnetic Field Strength)
ρ	Electrical Resistivity
RC	Rockwell 'C' Hardness
σ	Electrical Conductivity
SI	International System of Units

Contents

1. Introduction

The specialised non-destructive inspection technique of magnetic rubber testing (MRT) has been used to detect fatigue cracks and other structural defects in high strength D6ac steel airframe components of the F-111 aircraft for over 30 years [1,2]. In certain applications, the technique has proved capable of reliably detecting fatigue cracks of 0.012″ or more in length with a probability of detection of greater than 90% [3].

Despite the apparent maturity of the technique, there remain a number of uncertainties in our understanding of MRT of D6ac steel, particularly in relation to the performance of MRT using residual magnetic fields and in specifying the magnetic fields required for particular inspections. These uncertainties cannot be resolved without detailed information on the magnetic properties of D6ac steel.

Following an extensive search, it became apparent that there was no detailed information on the magnetic properties of D6ac in the published scientific and technical literature. It was therefore necessary for DSTO to arrange to have these properties measured directly by supplying a test specimen to the Australian Government National Measurement Institute.

In this technical note, the magnetic properties of D6ac steel typical of RAAF F-111 aircraft construction are recorded. The electrical properties of D6ac are also reported together with formulae for the electromagnetic skin depth applicable to eddy-current non-destructive inspection (NDI) of D6ac. This information is a prerequisite for a more complete understanding of the application of MRT to critical F-111 airframe structure.

2. Specimen Preparation

D6ac test specimens were machined from ½″x 3 ½″ rectangular bar stock*, and heat treated to the same condition as components in the F-111 airframe [4]. The specimens were then straightened and centre-less ground to produce cylindrical rods with a length of 300 mm and diameter of 13.0 mm suitable for magnetic measurements (Figure 1).

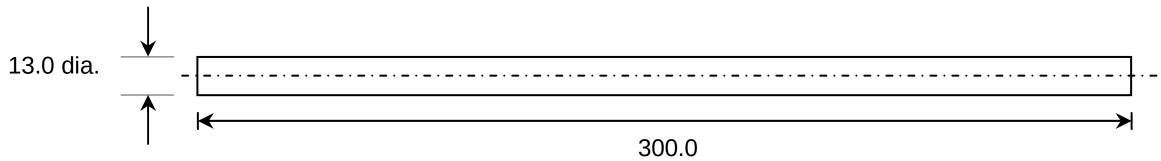

Figure 1. Dimensions (mm) of D6ac rods used for electrical and magnetic measurements

* Republic Steel (USA). Batch delivered Dec. 1971 & Jan. 1972. Ref: EM 39 AB1 and EM 39 AB2

3. Experimental Method

The normal induction curve and hysteresis loops were measured for D6ac steel in DC magnetic fields using a DC magnetic permeameter. The measurements were performed under contract to DSTO by the National Measurement Institute (NMI) situated at Lindfield, NSW. The results were provided to DSTO in the form of two written calibration reports traceable to the relevant Australian maintained standards of magnetic flux, electromotive force and resistance [5, 6]. Copies of the original reports are reproduced in Appendix B and Appendix C.

The measurements were made in accordance with the NMI test method AS/05/0007 which is based on ASTM Standard A341 [7]. The quoted uncertainties in the data are ± (30 A/m + 3%) in the magnetic field measurement and ± (0.5 mT + 3%) in the magnetic flux density measurement. All measurements were performed at 22.5 ± 1.0°C using the DSTO test specimen D6ac-100.

The electrical conductivity of D6ac steel was measured at DSTO for the same specimen using a standard 4-point method. In these measurements, a known DC current was injected at either end of the D6ac rod and the conductivity was deduced from measurements of the potential difference at a range of contact points separated by 140–170 mm along the midsection of the rod. The nominal temperature for these measurements was 20°C.

4. System of Units

Although out-dated, the Gaussian CGS system of units for magnetism is used in this report because this system is still used by RAAF NDTSL in the specification of MRT inspection procedures. The corresponding SI units are included throughout this report in keeping with required scientific practice. The two systems of units are compared in Table 1 and the appropriate conversion factors are as follows

1 Oersted (Oe) = 79.58 A/m
1 Gauss (G) = 0.1 mT

Table 1. Brief comparison of the SI and CGS units in magnetism [8]. In the SI system, $\mu_0 = 4\pi \times 10^{-7}$ H/m is the permeability of free space.

Quantity	SI (Sommerfeld)	CGS (Gaussian)
magnetic flux density **B** (magnetic induction)	Tesla	Gauss
magnetic field strength **H**	Ampere/meter	Oersted
magnetisation **M**	Ampere/meter	emu/cm^3
Field equation	$\mathbf{B} = \mu_0 (\mathbf{H}+\mathbf{M})$	$\mathbf{B} = \mathbf{H}+4\pi\mathbf{M}$

In air, the magnetic induction (*B*) is directly proportional to the magnetic field strength (*H*) because the magnetisation of the air (*M*) is negligible. For this reason, the "magnetic field" in air is frequently measured and reported using the units for *B* (Gauss or Tesla). In the CGS system of units, a magnetic field strength (*H*) of 1 Oersted (Oe) measured in air corresponds to a magnetic flux density in air (*B*) of 1 Gauss.

5. Magnetic Properties of D6ac Steel

The normal induction curve and a series of hysteresis curves for D6ac were measured by the Low Frequency Electrical and Magnetic Quantities Calibration Services of NMI as described in Section 3. The results are reproduced in this section, together with values of the key derived magnetic quantities.

5.1 Normal Induction Curve

The normal induction curve for D6ac was determined for magnetic field strengths from zero to 20 kA/m (~ 250 Oe), with the specimen demagnetised prior to taking measurements. The results are plotted in Figure 2 and are reproduced in Table A1.

5.2 Hysteresis Curve

Following the normal induction test, the complete hysteresis curve for D6ac was determined for magnetic field strengths ranging from +20 kA/m to -20 kA/m (or ~ - 250 Oe to +250 Oe). The results are plotted in Figure 3 and are reproduced in Table A2

5.3 Coercive Force, Remanence and Magnetic Permeability

A number of important magnetic properties were derived from the normal induction and hysteresis curves. From examination of the hysteresis curves in Figure 3, the magnetic remanence is 1.28 T and the coercive force is 2010 A/m or 25.2 Oe.

The relative magnetic permeability† μ_r was calculated from the normal induction curve data (Section 5.1) using the definition

$$\mu_r = B/(\mu_0 H) \qquad (1)$$

where, for SI units, *B* is the magnetic flux density (T), *H* is the magnetic field strength (A/m) and $\mu_0 = 4\pi \times 10^{-7}$ H/m is the permeability of free space. The results are shown as a function of magnetic field strength in Figure 4. The initial relative magnetic permeability for D6ac $\mu_i = 77 \pm 2$ was estimated by polynomial extrapolation of the data in Figure 4 to zero magnetic field. The maximum permeability μ_{max} =350 is observed at an applied magnetic field strength of 2700 A/m or 34 Oe.

† Also referred to as the "secant permeability"

The differential relative magnetic permeability

$$\mu_r' = \frac{1}{\mu_0}\frac{dB}{dH} \tag{2}$$

was also calculated from the normal induction curve data using a smoothing algorithm to compute the numerical derivative from the experimental data. The results are also presented in Figure 4. The maximum differential permeability μ_{max} =650 occurs at a magnetic field strength of 2150 A/m or 27 Oe.

These magnetic properties are summarised in Table 2

Table 2. Magnetic properties of D6ac steel

	SI units	CGS Units
Coercive force H_c	2010 A/m	25.2 Oersted
Remanent flux density B_r	1.28 T	12.8 kGauss
Initial magnetic permeability μ_i	77 ± 2	77 ± 2
Maximum permeability μ_{max}	μ_{max} =350 at 2700 A/m	μ_{max} =350 at 34 Oersted
Maximum differential magnetic permeability μ'_{max}	μ'_{max} =650 at 2150 A/m	μ'_{max} =650 at 27 Oersted

5.4 Minor Hysteresis Loops

A set of three minor hysteresis curves for D6ac was also measured. These curves were determined by demagnetising the specimen, applying a magnetic field H_{max} and then measuring the complete B-H loop on cycling the magnetic field strength from + H_{max} to -H_{max} and returning to + H_{max} . The values of H_{max} = 1600 A/m, 2400 A/m and 3700 A/m (20 Oe, 30 Oe and 46.5 Oe) were chosen to span a range of magnetic field strengths in the vicinity of H_c and include the fields typically encountered in MRT. The minor hysteresis loops are plotted in Figure 5 and are tabulated in Tables A3 to A5.

5.5 Variation of Remanence with Maximum Magnetic Field Strength

The relationship between the remanent magnetic flux density B_r and the maximum applied magnetic field strength H_{max} can be deduced from the hysteresis curves in Section 5.2 and Section 5.4. The results are shown in Figure 6. For residual field MRT, the more significant quantity is the rate of change of the magnetic remanence with H_{max}

$$\frac{1}{\mu_0}\frac{dB_r}{dH_{max}}. \tag{3}$$

This quantity is plotted in Figure 7 . The maximum rate of change is greater than 400 and occurs at a magnetic field strength in the vicinity of 2000 A/m or 25 Oe.

6. Significance for MRT

According to the literature for magnetic test methods, the maximum sensitivity for detection of surface-breaking defects using active field magnetic particle inspection (MPI) occurs for values of H in the vicinity of the inflection point (or knee) of the B-H curve [9] or, equivalently, in the vicinity of the peak in the magnetic permeability [10]. For D6ac, the inflection point in the normal curve data (Figure 2) or the peak in the differential permeability (Figure 4) occurs for magnetic field strength of ~ 27 Oe , corresponding to a tangential component of B at the surface of the test specimen of ~27 Gauss. This value is consistent with the recommendations of MRT/GEN/1 [2] for a value between 25-30 Gauss for active field inspections of bare surfaces.

For residual field inspections, the available literature [10] suggests that the applied magnetic field (H_{max}) should be chosen to lie to the right of the peak value in the rate of change of the magnetic remanence with H_{max}. According to the data in Figure 7, the applied field used for residual field MRT (if it is attempted at all) should exceed 50 Gauss. However, there are additional complicated geometric factors associated with determination of an adequate remanent magnetisation for MRT using residual fields.

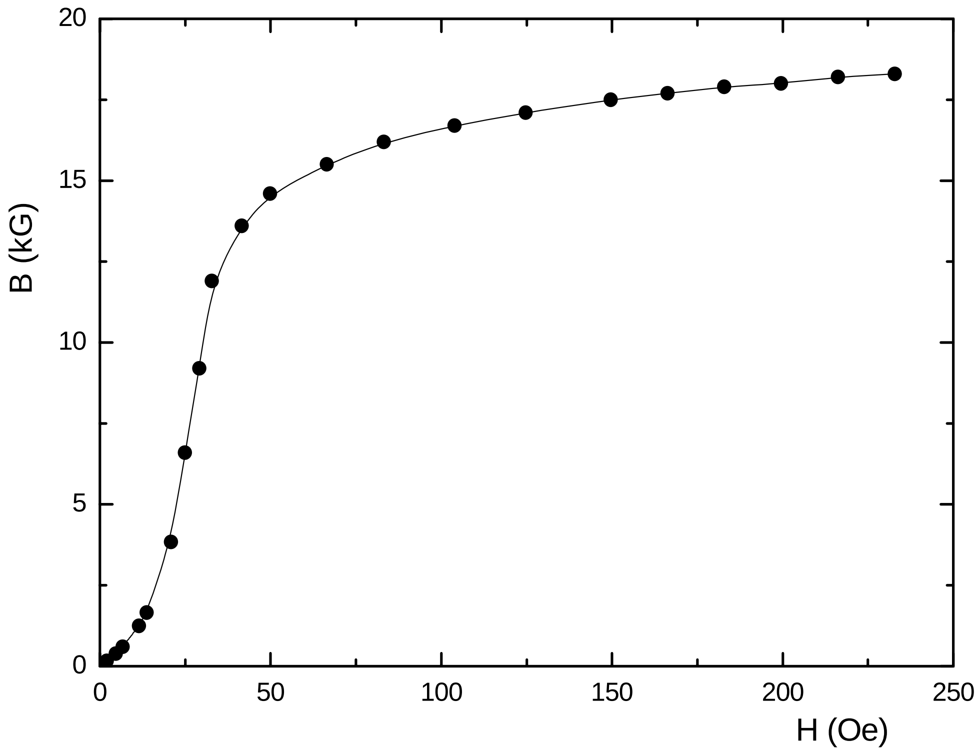

Figure 2. Normal magnetic induction curve for D6ac (CGS units)

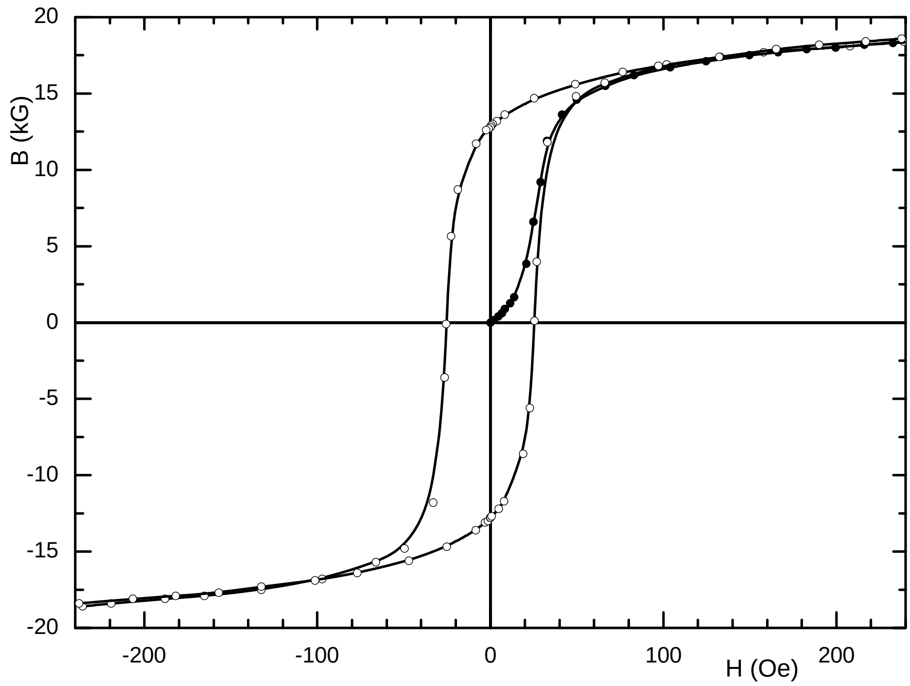

Figure 3. Hysteresis curve for D6ac (CGS units). The normal curve (closed symbols) is also shown for comparison.

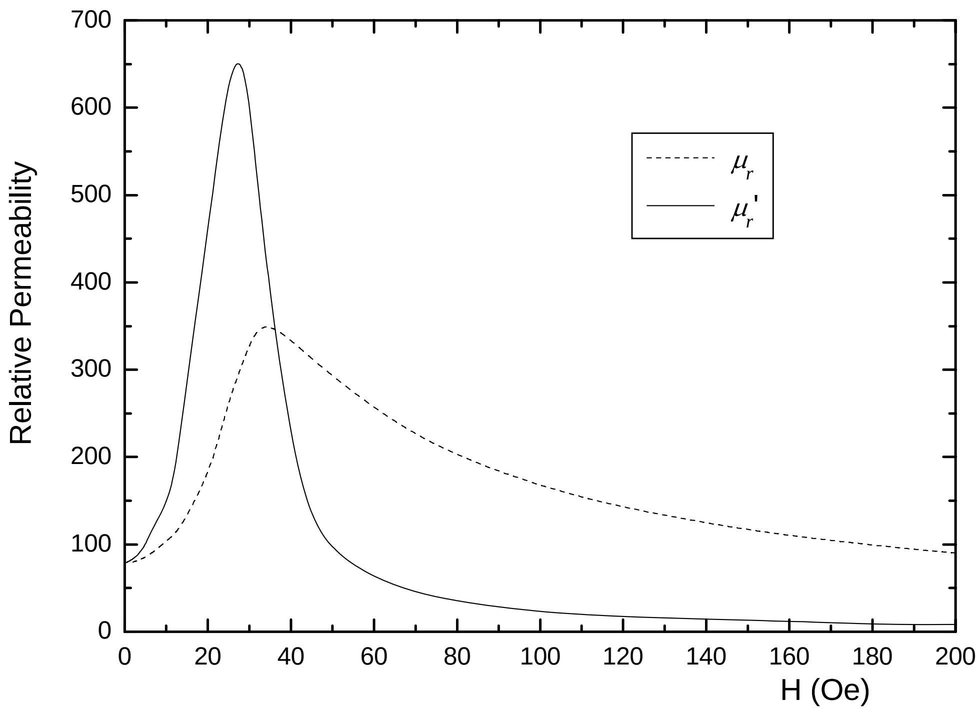

Figure 4. Relative magnetic permeability (broken curve) for D6ac as a function of magnetic field strength (CGS units) deduced from the normal induction curve Figure 2 using Eq. (1). The solid curve is the differential magnetic permeability, calculated from Eq. (2).

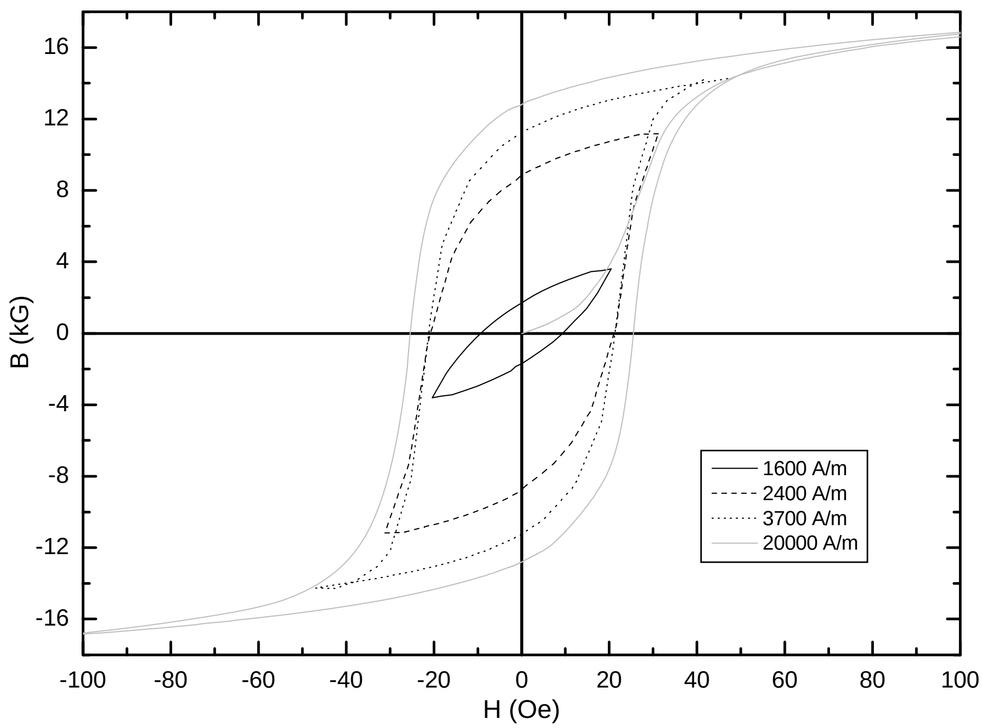

Figure 5. Minor hysteresis loops for D6ac (CGS units)

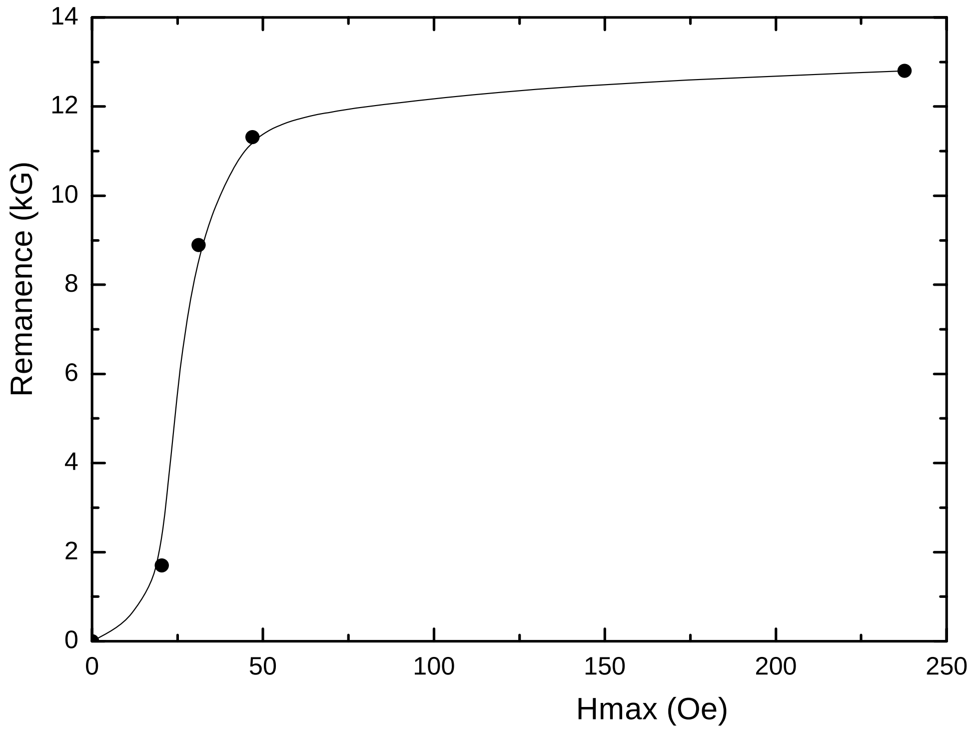

Figure 6. Variation of remanent magnetic flux density with the maximum applied magnetic field strength for D6ac steel (solid points). The curve has been inserted as a visual guide.

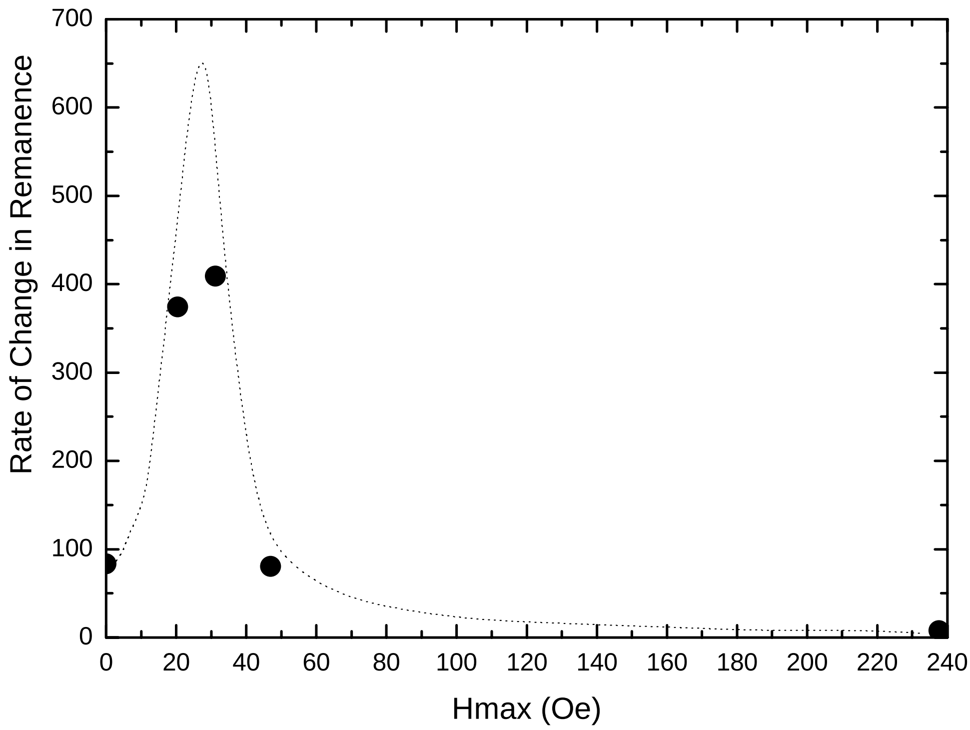

Figure 7. The rate of change in remanent magnetic flux density with maximum applied magnetic field strength (solid symbols) from Figure 6 and Eq. (3). The dotted curve is the variation of the differential magnetic permeability with applied field from Figure 4 and is included for comparison. The peak in the rate of change of remanence and the peak in the differential permeability occur at a similar magnetic field strength.

7. Comparison with SAE 4340 steel

SAE 4340 steel has previously been substituted for D6ac in magnetic-related studies, as having similar properties. Magnetic hysteresis loops for the two steels are compared in Figure 8 using the published results [11] for SAE 4340 heat-treated to Rockwell 'C' hardness RC=53.

Whilst the curves are similar in general form and magnitude, there are important differences in the magnetic properties between these two steels. The coercive force and magnetic remanence of SAE 4340 are lower than those of D6ac (Figure 8a). At lower applied magnetic field strengths, the properties differ quite significantly (Figure 8b), and on this basis, SAE 4340 steel should not be substituted for D6ac steel for the development of MRT inspection procedures. Furthermore, recommendations for magnetic particle inspection of SAE4340 cannot be applied directly to magnetic rubber or magnetic particle inspection of D6ac.

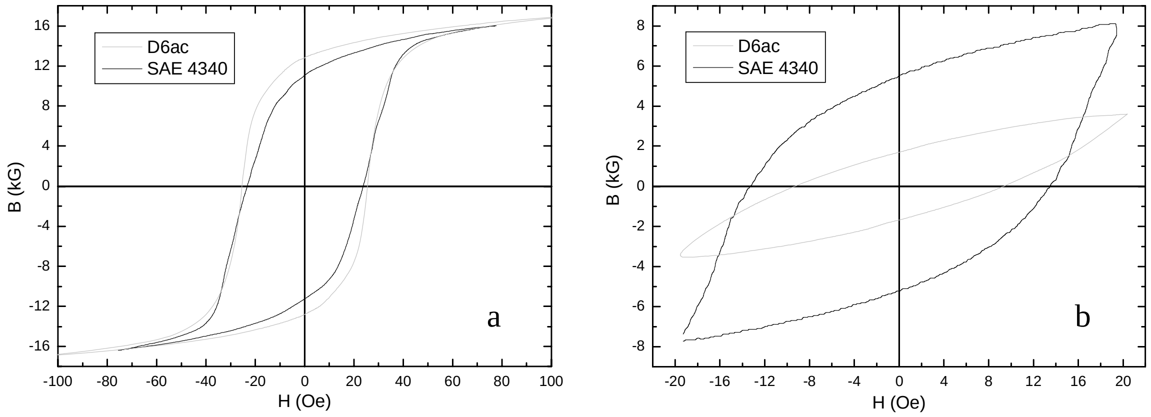

Figure 8. Comparison of the measured hysteresis loops for SAE 4340 [12] and D6ac steel for high and low fields. Note the scales differ in (a) and (b).

8. Electrical Properties of D6ac Steel

8.1 Electrical Conductivity

The measured DC electrical conductivity σ of D6ac at a nominal temperature of 20ºC is 3.57 MS/m or 6.15% IACS, corresponding to an electrical resistivity ρ = 28.0 μΩcm. This value is consistent with other high strength steels.

8.2 Skin Depth

The electromagnetic skin depth δ, or standard depth of penetration in mm, is defined in terms of the electrical resistivity ρ (μΩcm), relative magnetic permeability μ_r and frequency f (Hz) by the relationship

$$\delta = 50.3\sqrt{\rho/(\mu_r f)} \tag{4}$$

For D6ac, the magnetic permeability and hence the skin depth will depend on the magnitude of the applied field (Figure 4). The two most important cases in eddy-current NDT are for (i) a demagnetised specimen in zero applied field, for which μ_r=77, and (ii) when the steel is magnetically saturated and μ_r =1. In both these cases, the skin depth is given as a function of frequency by the equations‡

$$\delta = \begin{cases} 30.3/\sqrt{f} & \text{zero applied field} \\ 266.2/\sqrt{f} & \text{saturating applied field} \end{cases} \tag{5}$$

‡ A linear approximation is valid for D6ac provided the AC eddy-current probe magnetic flux density is less than ~0.5 mT

where, as in equation (4), δ is in units of mm and f in Hz. Thus, for D6ac at a given frequency, the skin depth increases by a factor of 9 in the presence of a saturating field (Figure 9). This may be either a disadvantage or an advantage depending on the eddy-current probe geometry and the inspection application.

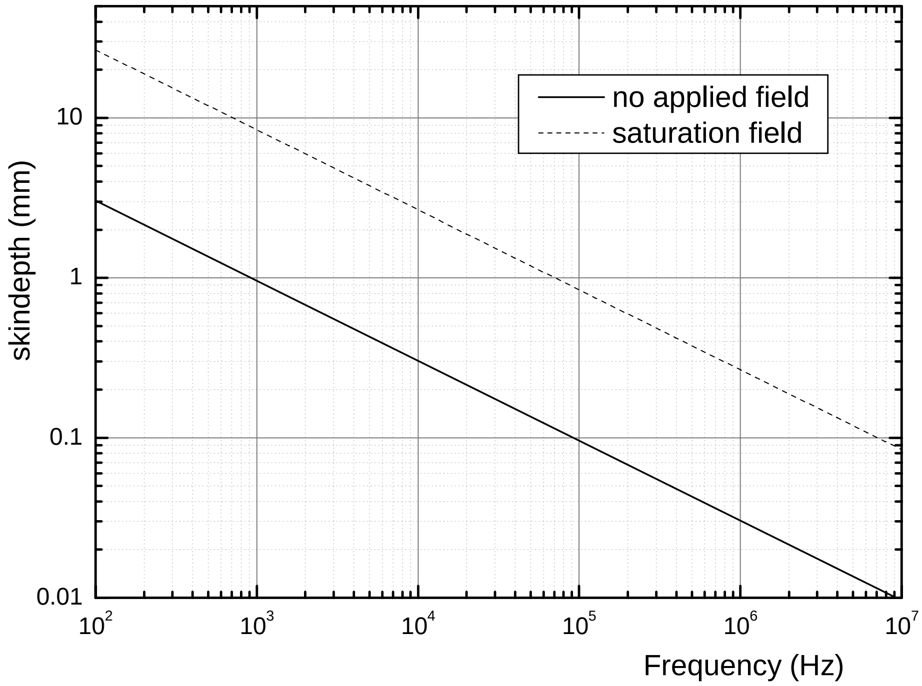

Figure 9. Calculated skin depth as a function of frequency for eddy-current NDT of D6ac. The solid line is for a D6ac specimen which has been demagnetised and has not been subject to an applied DC field. The broken line is for a D6ac specimen which is magnetically saturated. In both cases, the AC field due to the eddy-current probe is assumed to be small (less than 0.5 mT).

9. Conclusion

The magnetic properties of D6ac steel of the same stock as that used in the RAAF F-111 fleet, and having identical heat treatment, have been accurately determined and are now available as a reference for future work. The magnetic and electrical properties were found to be similar in general form to those of other high-strength steels, such as SAE 4340. However they were not sufficiently alike that other steels may be substituted when developing or validating electromagnetic test procedures intended for D6ac components.

The understanding of the magnetic properties of D6ac steel obtained from these measurements give a fundamental basis to limitations and specifications used in MRT, and thus give increased confidence in the determination of appropriate settings to be used in procedure development for the future.

10. Acknowledgements

The authors acknowledge the expertise and scientific services of Mr Vasukan Balakrishnan of Low Frequency Electrical and Magnetic Quantities Calibration Services, National Measurement Institute, Lindfield, NSW in performing the magnetic measurements central to this work.

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Appendix A: Tabulation of Results

A.1 Normal Induction Curve for D6ac

Table A1. Normal Curve

H (A/m)	B (Tesla)	H (Oe)	B (kGauss)
0	0	0	0
160	0.016	2.01	0.16
369	0.039	4.64	0.39
529	0.06	6.65	0.60
665	0.089	8.36	0.89
910	0.125	11.44	1.25
1093	0.166	13.73	1.66
1654	0.384	20.78	3.84
1985	0.66	24.94	6.60
2316	0.92	29.10	9.20
2614	1.19	32.85	11.9
3308	1.36	41.57	13.6
3970	1.46	49.89	14.6
5293	1.55	66.51	15.5
6617	1.62	83.15	16.2
8271	1.67	103.93	16.7
9925	1.71	124.72	17.1
11910	1.75	149.66	17.5
13234	1.77	166.30	17.7
14557	1.79	182.92	17.9
15880	1.8	199.55	18.0
17204	1.82	216.18	18.2
18527	1.83	232.81	18.3
19850	1.84	249.43	18.4
20181	1.85	253.59	18.5

A.2 Hysteresis Curves for D6ac

Table A2. 20 kA/m Curves

Descending curve				Ascending curve			
H (A/m)	B (T)	H(Oe)	B(kGauss)	H (A/m)	B (T)	H(Oe)	B(kGauss)
20181	1.85	253.59	18.5	-18913	-1.84	-237.66	-18.4
19023	1.84	239.04	18.4	-16446	-1.81	-206.66	-18.1
16542	1.81	207.87	18.1	-14473	-1.79	-181.87	-17.9
14557	1.79	182.92	17.9	-12499	-1.77	-157.06	-17.7
12572	1.77	157.98	17.7	-10526	-1.73	-132.27	-17.3
10587	1.74	133.03	17.4	-8059	-1.69	-101.27	-16.9
8106	1.69	101.86	16.9	-6118	-1.64	-76.88	-16.4
6087	1.64	76.49	16.4	-3750	-1.56	-47.12	-15.6
3904	1.56	49.058	15.6	-2006	-1.47	-25.21	-14.7
2018	1.47	25.36	14.7	-661	-1.36	-8.31	-13.6
665	1.36	8.36	13.6	-237	-1.31	-2.98	-13.1
311	1.32	3.91	13.2	-112	-1.3	-1.41	-13
101	1.3	1.27	13	-13	-1.28	-0.16	-12.8
46	1.29	0.58	12.9	16	-1.28	0.20	-12.8
0	1.28	0	12.8	54	-1.27	0.68	-12.7
-76	1.27	-0.96	12.7	382	-1.22	4.80	-12.2
-197	1.26	-2.48	12.6	638	-1.17	8.02	-11.7
-651	1.17	-8.18	11.7	1513	-0.86	19.01	-8.6
-1497	0.87	-18.81	8.7	1826	-0.561	22.94	-5.61
-1809	0.566	-22.73	5.66	2039	0.011	25.62	0.11
-2039	-0.011	-25.62	-0.11	2138	0.397	26.87	3.97
-2105	-0.36	-26.45	-3.6	2631	1.18	33.06	11.8
-2631	-1.18	-33.06	-11.8	3947	1.48	49.60	14.8
-3947	-1.48	-49.60	-14.8	5263	1.57	66.13	15.7
-5263	-1.57	-66.13	-15.7	7730	1.68	97.13	16.8
-7730	-1.68	-97.13	-16.8	10526	1.74	132.27	17.4
-10526	-1.75	-132.27	-17.5	13157	1.79	165.33	17.9
-13157	-1.79	-165.33	-17.9	15131	1.82	190.13	18.2
-14966	-1.81	-188.06	-18.1	17269	1.84	217.00	18.4
-17433	-1.84	-219.06	-18.4	18913	1.86	237.66	18.6

Table A3. 3700 A/m Curves

H (A/m)	B (T)	H (Oe)	B (kGauss)
3738	1.426	46.97	14.26
2746	1.378	34.51	13.78
2002	1.333	25.16	13.33
1505	1.298	18.91	12.98
1009	1.255	12.68	12.55
599	1.211	7.53	12.11
36	1.131	0.45	11.31
-397	1.042	-4.99	10.42
-959	0.85	-12.05	8.5
-1439	0.501	-18.08	5.01
-1654	0.093	-20.78	0.93
-2002	-0.806	-25.16	-8.06
-2382	-1.216	-29.93	-12.16
-2614	-1.303	-32.85	-13.03
-3044	-1.391	-38.25	-13.91
-3375	-1.429	-42.41	-14.29
-3738	-1.426	-46.97	-14.26
-2729	-1.378	-34.29	-13.78
-2002	-1.334	-25.16	-13.34
-1505	-1.299	-18.91	-12.99
-1009	-1.256	-12.68	-12.56
-592	-1.211	-7.44	-12.11
-30	-1.131	-0.38	-11.31
404	-1.041	5.077	-10.41
966	-0.85	12.14	-8.5
1442	-0.497	18.12	-4.97
1667	-0.071	20.95	-0.71
2018	0.818	25.36	8.18
2382	1.2	29.93	12
2647	1.306	33.26	13.06
3044	1.381	38.25	13.81
3375	1.431	42.41	14.31

Table A4. 2400 A/m Curves

H (A/m)	B (T)	H (Oe)	B (kGauss)
2481	1.117	31.18	11.17
2117	1.113	26.60	11.13
1720	1.084	21.61	10.84
1323	1.051	16.63	10.51
877	1.008	11.02	10.08
589	0.973	7.40	9.73
318	0.936	4.00	9.36
14	0.889	0.176	8.89
-109	0.855	-1.37	8.55
-377	0.798	-4.74	7.98
-602	0.736	-7.56	7.36
-926	0.622	-11.64	6.22
-1257	0.433	-15.80	4.33
-1704	-0.058	-21.41	-0.58
-1952	-0.552	-24.53	-5.52
-2051	-0.732	-25.77	-7.32
-2481	-1.117	-31.18	-11.17
-2117	-1.113	-26.60	-11.13
-1753	-1.083	-22.03	-10.83
-1356	-1.051	-17.04	-10.51
-893	-1.005	-11.22	-10.05
-602	-0.969	-7.56	-9.69
-337	-0.935	-4.23	-9.35
-35	-0.886	-0.44	-8.86
93	-0.849	1.17	-8.49
357	-0.787	4.49	-7.87
592	-0.726	7.44	-7.26
893	-0.616	11.22	-6.16
1257	-0.43	15.80	-4.3
1720	0.046	21.61	0.46
1952	0.557	24.53	5.57
2051	0.728	25.77	7.28
2481	1.117	31.18	11.17

Table A5. 1600 A/m Curves

H (A/m)	B (T)	H (Oe)	B (kGauss)
1621	0.36	20.37	3.6
1462	0.353	18.37	3.53
1257	0.345	15.80	3.45
993	0.317	12.48	3.17
794	0.295	9.98	2.95
529	0.258	6.65	2.58
341	0.232	4.29	2.32
205	0.211	2.58	2.11
111	0.191	1.39	1.91
2	0.17	0.03	1.7
-136	0.145	-1.71	1.45
-331	0.104	-4.16	1.04
-549	0.052	-6.90	0.52
-734	0.004	-9.22	0.04
-976	-0.072	-12.26	-0.72
-1075	-0.107	-13.51	-1.07
-1158	-0.139	-14.55	-1.39
-1370	-0.225	-17.22	-2.25
-1621	-0.36	-20.37	-3.6
-1462	-0.353	-18.37	-3.53
-1257	-0.344	-15.80	-3.44
-993	-0.315	-12.48	-3.15
-794	-0.295	-9.98	-2.95
-526	-0.259	-6.61	-2.59
-334	-0.232	-4.20	-2.32
-199	-0.21	-2.50	-2.1
-108	-0.185	-1.36	-1.85
9	-0.167	0.11	-1.67
146	-0.14	1.83	-1.4
341	-0.101	4.29	-1.01
569	-0.049	7.15	-0.49
741	-0.003	9.31	-0.03
959	0.069	12.05	0.69
1092	0.11	13.72	1.1
1174	0.138	14.75	1.38
1373	0.226	17.25	2.26
1621	0.36	20.37	3.6

Appendix B: NMI Measurement Report RN48153

Copy of *Measurement Report on Steel Rod Sample Serial Number D6AC-100 Normal Induction and Hysteresis Curves*, National Measurement Institute, Lindfield, NSW, Ref: RN48153 File CB/04/0347 07 February 2005. Reproduced in full.

Australian Government

National Measurement Institute

MEASUREMENT REPORT ON

Steel Rod Sample

Serial number D6AC-100

Normal Induction and Hysteresis Curves

The National Measurement Institute is responsible for Australia's units and standards of measurement. The measurement results presented in this report are traceable to Australia's primary standards.

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Ref: RN48153 File: CB/04/0347 Checked: VB Date: 7 February 2005

Description	:	Steel rod sample; 12.05 mm diameter x 300 mm long
Manufacturer	:	DSTO
Serial number	:	D6AC-100
Client	:	DSTO Aeronautical and Maritime Research Laboratory 506 Lorimer Street Fishermans Bend VIC 3207
Reference	:	Quotation no. 7867, accepted 18/11/2004
Date of test	:	14/1/2005 to 3/2/2005
Air Temperature		(22.5 ± 1.0) ° C
Relative Humidity		(50 ± 10) %
Testing officer	:	V. Balakrishnan

Uncertainty:

The uncertainty has been calculated in accordance with principles in the ISO Guide to the Expression of Uncertainty in Measurement, and gives an interval estimated to have a level of confidence of 95%. The coverage factor is 2.0.

The uncertainties apply at the time of measurement only and take no account of any drift or other effects that may apply afterwards. When estimating the uncertainties at any later time, other relevant information should also be considered, including, where possible, the history of the performance of the sample and the manufacturer's specifications.

Traceability:

All quantities applied to the measurements were traceable to the relevant Australian maintained standards of magnetic flux, electromotive force and resistance.

Test procedure:

The measurements were made in accordance with the NMI documented Test method which is based on the ASTM Standard A341.

…/Page 3

Results:

1. Normal Induction Curve:

The sample was demagnetised prior to the start of the measurements.

Magnetic flux densities of the sample corresponding to magnetic field strengths from zero to 20 000 A/m are listed in Table 1 and presented as a graph on Page 7.

Table 1

Magnetic Field Strength *(A/m)*	**Magnetic Flux Density** *(T)*
160	0.016
369	0.039
529	0.060
665	0.089
910	0.125
1 093	0.166
1 654	0.384
1 985	0.66
2 316	0.92
2 614	1.19
3 308	1.36
3 970	1.46
5 293	1.55
6 617	1.62
8 271	1.67
9 925	1.71
11 910	1.75
13 234	1.77
14 557	1.79
15 880	1.80
17 204	1.82
18 527	1.83
19 850	1.84
20 181	1.85

…/Page 4

2. Hysteresis Curve:

After the Normal Induction Curve test, the full B-H loop was traced, with the magnetic field strength ranging from 20 000 A/m to −20 000 A/m. The data is listed in Table 2 and presented as a graph on Page 8.

Table 2

Magnetic Field Strength *(A/m)*	**Magnetic Flux Density** *(T)*
+ 20 181	1.85
+ 19 023	1.84
+ 16 542	1.81
+ 14 557	1.79
+ 12 572	1.77
+ 10 587	1.74
+ 8 106	1.69
+ 6 087	1.64
+ 3 904	1.56
+ 2 018	1.47
+ 665	1.36
+ 311	1.32
+ 101	1.30
+ 46	1.29
0	1.28
−76	1.27
−197	1.26
−651	1.17
−1 497	0.87
−1 809	0.566
−2 039	-0.011
−2 105	-0.360
−2 631	-1.18
−3 947	-1.48
−5 263	-1.57
−7 730	-1.68
−10 526	-1.75
−13 157	-1.79
−14 966	-1.81
−17 433	-1.84
−18 749	-1.86

…/Page 5

Continuation of Measurement Report on
Steel Rod Sample, serial number D6AC-100

Table 2 Continued

Magnetic Field Strength *(A/m)*	**Magnetic Flux Density** *(T)*
−18 913	-1.84
−16 446	-1.81
−14 473	-1.79
−12 499	-1.77
−10 526	-1.73
−8 059	-1.69
−6 118	-1.64
−3 750	-1.56
−2 006	-1.47
−661	-1.36
−237	-1.31
−112	-1.30
−13	-1.28
+ 16	-1.28
+ 54	-1.27
+ 382	-1.22
+ 638	-1.17
+ 1 513	-0.86
+ 1 826	-0.561
+ 2 039	0.011
+ 2 138	0.397
+ 2 631	1.18
+ 3 947	1.48
+ 5 263	1.57
+ 7 730	1.68
+ 10 526	1.74
+ 13 157	1.79
+ 15 131	1.82
+ 17 269	1.84
+ 18 913	1.86

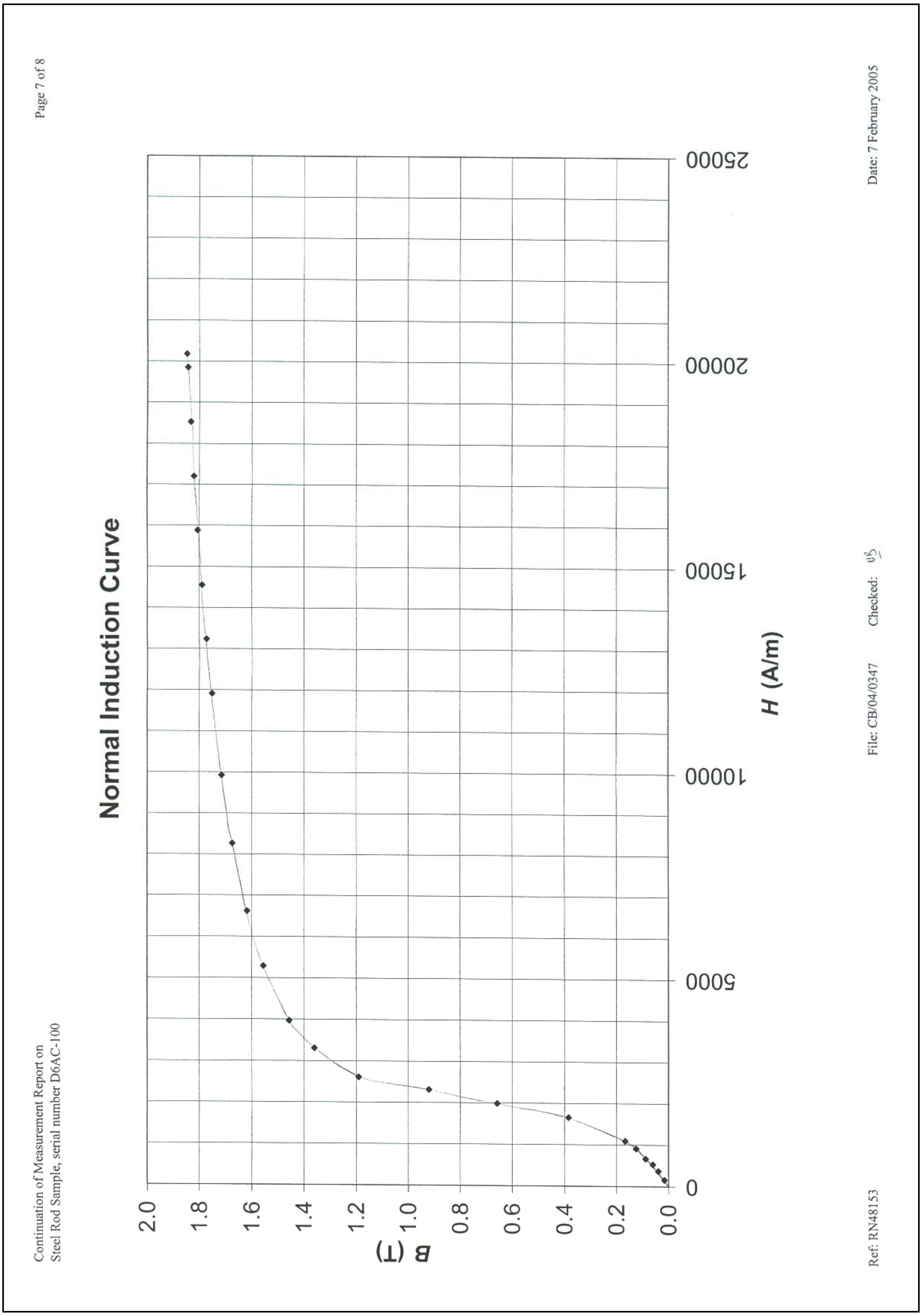
…/Page 6

The sample's remanence and coercive force are 1.28 T and 2 010 A/m respectively.

The estimated uncertainty in the magnetic field measurement is ± (30 A/m + 3 %).
The estimated uncertainty in the magnetic flux density measurement is ± (0.5 mT + 3 %).

Dr I. F. Budovsky
for Dr B. D. Inglis
Chief Metrologist

Ref: RN48153 File: CB/04/0347 Checked: VB Date: 7 February 2005


Continuation of Measurement Report on
Steel Rod Sample, serial number D6AC-100
Page 7 of 8
Normal Induction Curve
B (T)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5000
10000
15000
20000
25000
H (A/m)
Ref: RN48153
File: CB/04/0347
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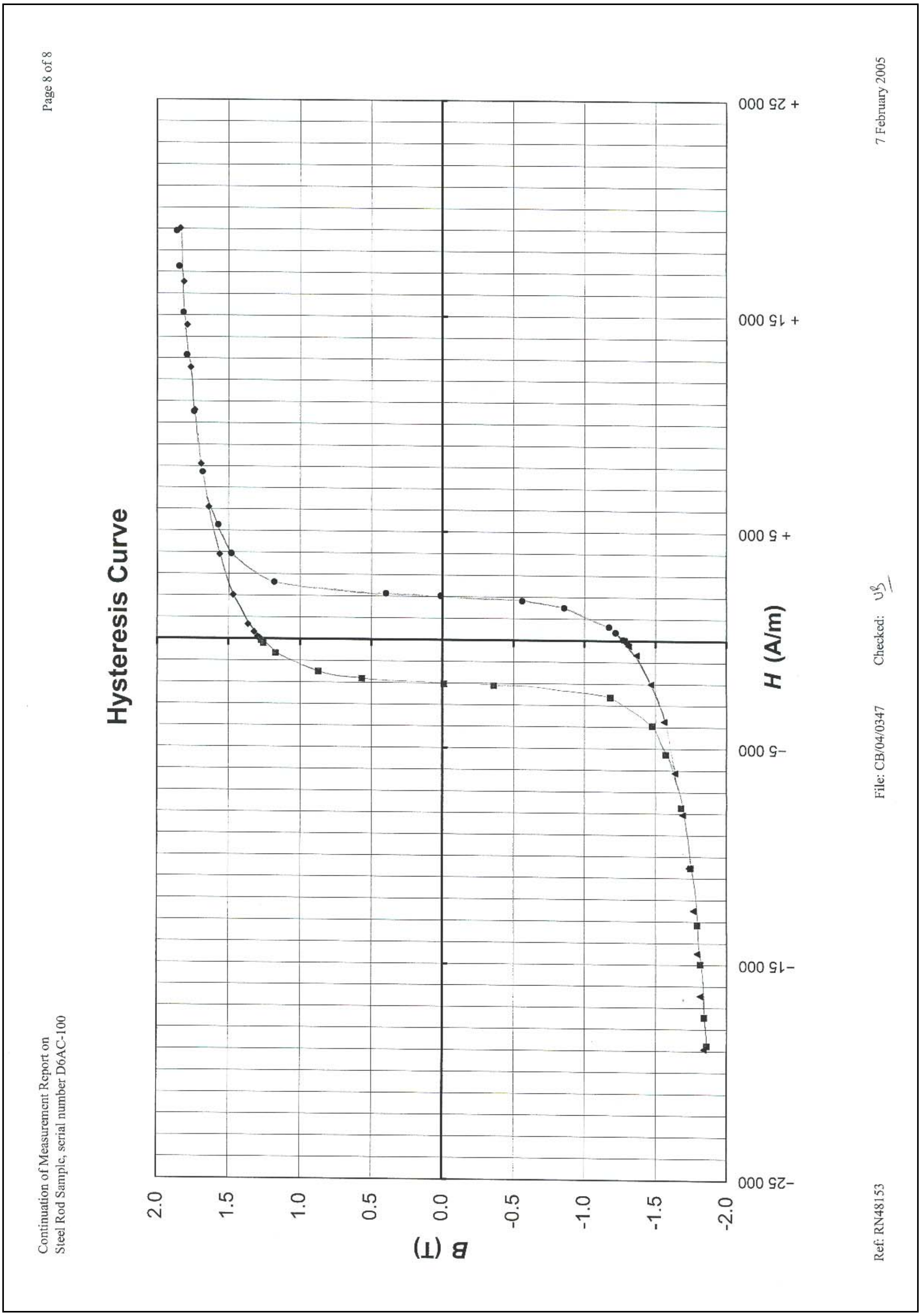
Date: 7 February 2005



Page 8 of 8
Hysteresis Curve
Continuation of Measurement Report on
Steel Rod Sample, serial number D6AC-100
B (T)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
H (A/m)
−25 000
−15 000
−5 000
+ 5 000
+ 15 000
+ 25 000
Ref: RN48153
File: CB/04/0347
Checked:
7 February 2005

Appendix C: NMI Measurement Report RN48592

Copy of *Measurement Report on Steel Rod Sample Serial Number D6AC-100 B-H Loops at 1600, 2400 and 3700 A/m Fields*, National Measurement Institute, Lindfield, NSW, Ref: RN48592 File CB/04/0347 19 April 2005. Reproduced in full.

Australian Government

National Measurement Institute

MEASUREMENT REPORT ON

Steel Rod Sample

Serial number D6AC-100

B-H loops at 1 600, 2 400 and 3 700 A/m fields

The National Measurement Institute is responsible for Australia's units and standards of measurement. The measurement results presented in this report are traceable to Australia's primary standards.

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Ref: RN48592 File: CB/04/0347 Checked: Date: 19 April 2005

Description	:	Steel rod sample; 12.05 mm diameter x 300 mm long
Manufacturer	:	DSTO
Serial number	:	D6AC-100
Client	:	DSTO Aeronautical and Maritime Research Laboratory 506 Lorimer Street Fishermans Bend VIC 3207
Reference	:	Quotation no. 8472, accepted 23/3/2005
Date of test	:	11/4/2005 to 18/4/2005
Air Temperature		(22.5 ± 1.0) ° C
Relative Humidity		(50 ± 10) %
Testing officer	:	V. Balakrishnan

Traceability:

All quantities applied to the measurements were traceable to the relevant Australian maintained standards of magnetic flux, electromotive force and resistance.

Test procedure:

The measurements were made in accordance with the NMI documented Test method AS/05/0007, which is based on the ASTM Standard A341.

Prior to each test the sample was demagnetised. The sample was subjected to the test fields 1 600, 2 400 and 3 700 A/m and then the respective B-H loop was traced.
The observed data are listed in Tables 1, 2 and 3.

…/Page 3

Continuation of Measurement Report on
Steel Rod Sample, serial number D6AC-100

Table 1: **1 600 A/m**

Magnetic Field Strength *(A/m)*	**Magnetic Flux Density** *(T)*
+ 1 621	+ 0.360
+ 1 462	+ 0.353
+ 1 257	+ 0.345
+ 993	+ 0.317
+ 794	+ 0.295
+ 529	+ 0.258
+ 341	+ 0.232
+ 205	+ 0.211
+ 111	+ 0.191
+ 2	+ 0.170
− 136	+ 0.145
− 331	+ 0.104
− 549	+ 0.052
− 734	+ 0.004
− 976	− 0.072
−1 075	− 0.107
−1 158	− 0.139
−1 370	− 0.225
−1 621	− 0.360
−1 462	− 0.353
−1 257	− 0.344
− 993	− 0.315
− 794	− 0.295
− 526	− 0.259
− 334	− 0.232
− 199	− 0.210
− 108	− 0.185
+ 9	− 0.167
+ 146	− 0.140
+ 341	− 0.101
+ 569	− 0.049
+ 741	− 0.003
+ 959	+ 0.069
+ 1 092	+ 0.110
+ 1 174	+ 0.138
+ 1 373	+ 0.226

…/Page 4

Continuation of Measurement Report on
Steel Rod Sample, serial number D6AC-100

Table 2: **2 400 A/m**

Magnetic Field Strength *(A/m)*	**Magnetic Flux Density** *(T)*
+ 2 481	+ 1.117
+ 2 117	+ 1.113
+ 1 720	+ 1.084
+ 1 323	+ 1.051
+ 877	+ 1.008
+ 589	+ 0.973
+ 318	+ 0.936
+ 14	+ 0.889
− 109	+ 0.855
− 377	+ 0.798
− 602	+ 0.736
− 926	+ 0.622
− 1 257	+ 0.433
− 1 704	− 0.058
− 1 952	− 0.552
− 2 051	− 0.732
− 2 481	− 1.117
− 2 117	− 1.113
− 1 753	− 1.083
− 1 356	− 1.051
− 893	− 1.005
− 602	− 0.969
− 337	− 0.935
− 35	− 0.886
+ 93	− 0.849
+ 357	− 0.787
+ 592	− 0.726
+ 893	− 0.616
+ 1 257	− 0.430
+ 1 720	+ 0.046
+ 1 952	+ 0.557
+ 2 051	+ 0.728

…/Page 5

Ref: RN48592 File: CB/04/0347 Checked: SH Date: 19 April 2005

Continuation of Measurement Report on
Steel Rod Sample, serial number D6AC-100

Table 3: **3 700 A/m**

Magnetic Field Strength *(A/m)*	**Magnetic Flux Density** *(T)*
+ 3 738	+ 1.426
+ 2 746	+ 1.378
+ 2 002	+ 1.333
+ 1 505	+ 1.298
+ 1 009	+ 1.255
+ 599	+ 1.211
+ 36	+ 1.131
− 397	+ 1.042
− 959	+ 0.850
−1 439	+ 0.501
−1 654	+ 0.093
−2 002	− 0.806
−2 382	− 1.216
−2 614	− 1.303
−3 044	− 1.391
−3 375	− 1.429
−3 738	− 1.426
−2 729	− 1.378
−2 002	− 1.334
−1 505	− 1.299
−1 009	− 1.256
− 592	− 1.211
− 30	− 1.131
+ 404	− 1.041
+ 966	− 0.850
+ 1 442	− 0.497
+ 1 667	− 0.071
+ 2 018	+ 0.818
+ 2 382	+ 1.200
+ 2 647	+ 1.306
+ 3 044	+ 1.381
+ 3 375	+ 1.431

…/Page 6

Ref: RN48592 File: CB/04/0347 Checked: [signature] Date: 19 April 2005

Uncertainty:

The uncertainty has been calculated in accordance with principles in the ISO Guide to the Expression of Uncertainty in Measurement, and gives an interval estimated to have a level of confidence of 95%. The coverage factor is 2.0.

The uncertainties apply at the time of measurement only and take no account of any drift or other effects that may apply afterwards. When estimating the uncertainties at any later time, other relevant information should also be considered, including, where possible, the history of the performance of the sample and the manufacturer's specifications.

The estimated uncertainty in the magnetic field measurement is ± (30 A/m + 3 %).
The estimated uncertainty in the magnetic flux density measurement is ± (0.5 mT + 3 %).

Dr I. F. Budovsky
for Dr B. D. Inglis
Chief Metrologist

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Electrical properties, magnetic properties, steel, F-111 aircraft, non-destructive testing

19. ABSTRACT

The room temperature electrical and magnetic properties of the high strength steel D6ac are documented in this report. These data were used to support a wider study on the application of magnetic rubber testing (MRT) for the structural integrity management of the RAAF F-111 aircraft. While the immediate purpose of this report is to provide documented supporting data for MRT applied to the F-111 application, the results will also benefit more general investigations on the use of magnetic and electromagnetic methods for non-destructive testing of high-strength steels